Improved Reliability Testing with Multiaxial Electrodynamics Vibration

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SUMMARY & CONCLUSIONS

The functionality of next-generation DoD platforms, such as the Small Unmanned Ground Vehicles (SUGV) and Small Unmanned Arial Vehicles (SUAV), is strongly electronics-rich, Figure 1. Thus, the reliability of these systems will be strongly dependent on the reliability of the electronics. These electronic systems and the critical components in them experience extremely harsh environments such as vibration and thermal fatigue. Therefore, it is imperative to identify the failure mechanisms of these components through experimental and simulated failure assessment. One of the key challenges in re-creating life-cycle vibration conditions during design and qualification testing in the lab is the re-creation of simultaneous multi-axial excitation that the product experiences in the field. Instead, the common practice is to use sequential single-axis excitation in different axes or uncontrolled multi-axial vibration on repetitive shock shakers. Consequently, the dominant failure modes in the field are sometimes very difficult to duplicate in a laboratory test. The US Army Materiel Systems Analysis Activity (AMSAA) is currently collaborating with the Center of Advanced Life Cycle Engineering (CALCE) at the University of Maryland, to develop test methods that better capture unforeseen design defects in the qualification stage, by better replication of the life-cycle vibration conditions. This effort has led to utilizing a novel six degrees of freedom (DOF) electrodynamic shaker to ruggedize designs for fatigue damage due to random vibration.

Figure 1- SUGV, from iRobot Inc.

This paper discusses the merits of vibration testing methods with a six-DoF shaker and the cost saving associated with such an approach. The six DoF shaker may detect critical failures earlier in the development cycle than has been traditionally possible with existing shaker technologies; and therefore produce more cost effective and reliable systems for our warfighters.

1 INTRODUCTION

The increasing complexity of electronic equipment, especially in low volume and highly sophisticated and dense electronic systems, such as military, aerospace, and automotive applications, has resulted in an increased need to understand the failure mechanisms due to dynamic loads. Typically, electronic systems are subjected to various complex loadings, including vibration, during their life-cycle. Comprehending failure mechanisms due to dynamic loads can be achieved via accelerated vibration testing of electronic products. This offers great potential for improvements in reliability life testing while reducing testing time and cost. Unfortunately, difficulties encountered in accelerated life testing have limited its application and acceptance. Some of these difficulties can be traced, in part, to a lack of understanding of the actual failure mechanisms and sites in accelerated testing. To understand a particular failure mechanism by means of testing, it is important to simulate actual vibration conditions, which can be accomplished with a Physics of Failure (PoF) approach utilizing a multiaxial shaker.

The assumption was that there would be an abundance of research performed in this area since most mechanical and electronics products are universally subject to accelerations in all DoF. It was recognized that a great wealth of studies have been done on vibration testing using single and sequential uniaxial excitation. However, research performed in multiaxial vibration testing using electrodynamic shakers is extremely limited due to cost constraints associated with multiaxial vibration testing (French *et al.*, 2007).

Published standards requiring multi-axis vibration testing are almost nonexistent. The most common standards for

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vibration testing for military devices are published in MIL-STD-810F and NAVMAT P-9492 which contain both single and sequential testing but no mention of simultaneous multiaxial excitations. Therefore, for the past several decades, electrodynamic shakers have been the predominant vehicle for conducting random vibration testing of electronic and mechanical systems including aerospace, automotive, communication and military applications. Nonetheless, it is important to point out that sequential uniaxial testing does not provide a true manifestation of the actual operating environment of a test device (Whiteman and Berman, 2002).

2 CURRENT CHALLANGES

While several different schemes are widely used to test devices sequentially in the various axes, it is understood that they are rough approximations to the ideal of simultaneous multiaxis testing. Uniaxial excitations are applied to test objects even though most mechanical application data show that devices are subject to a multidirectional environment such as a spacecraft launch, a military ground vehicle deployment or a computer operating an automotive engine. Therefore, serious compromises must be made in the experimental design to perform meaningful tests on a single DoF electrodynamic shaker (Hobbs, 2001). For example, to simulate multi-DoF vibrations in military applications, MIL-STD-810F recommends performing the vibration tests by sequentially applying uniaxial excitation to a test object along three orthogonal axes (X, Y and Z). This is accomplished by exciting the test object vertically then repeating the procedure two more times after rotating the article 90^o each time. Figure 2 is an example of a sequential multiaxial Acceleration Power Density (ASD) profile for composite two wheeled Trailer Vibration according to MIL-STD-810F.

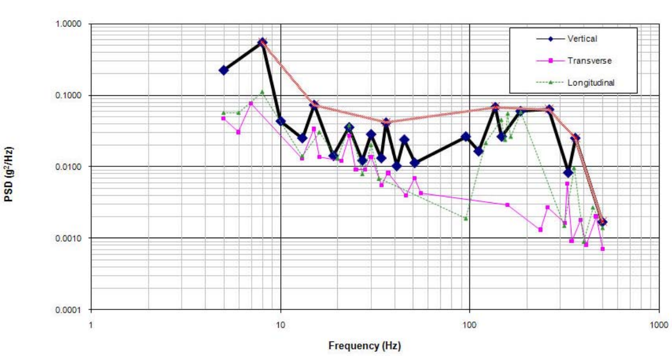

Figure 2 – Composite Two-Wheeled Trailer Vibration Profile

In aerospace applications, the majority of vibrations, acoustics and shocks stem from launch loads which are multiaxial in nature. One of the most critical and persistent design problems in spacecraft design is launch survival of the high precision, sensitive and expensive electronics systems. Johnson *et al.* (2001) states that the acceleration levels input to the spacecraft are over a wide frequency range from about 30 Hz to 2000 Hz or higher. Billions of dollars in lost satellites or degraded performance of precision payloads are attributed to failures arising from vibration due to launch loads (Sater *et al.*, 2000).

Multiaxial vibration problems also present serious and complex design challenges in micro-satellites. To control or mitigate the risk of vibration effects, complex systems and strategies are employed. Some typical solutions involve six-axial vibration systems with sophisticated isolators and multiple sensors (Thayer, 2002). Such complex solutions, however, can be costly and sometimes unnecessary. This radical approach can be avoided if the product in question is studied under multiaxial shakers to produce a clear understanding of the critical failure mode mechanisms. Such an understanding of multiaxial excitations enables designers to create robust and cost effective components and isolation systems that can withstand these harsh conditions.

Studies published in the open literature pertaining to single axial and multiaxial vibration testing for aerospace applications are limited. However, the automotive industry provides a plethora of literature in single and multi excitation testing. Components in automotive applications are subjected to fatigue testing to ensure they will not fail during the design life of the vehicle, typically 160,000 km, to meet the warranty obligation (Awate *et al.*, 2007). Typically, a test vehicle will be driven over a set of chosen road surfaces under expected driving conditions, while accelerations are measured on the component in question. These data are then brought into the laboratory to replicate the measured accelerations, thereby subjecting the component to the same fatigue conditions it experienced in the test vehicle. Depending on the location and application, a typical automobile component qualification test requires a 2.9 G_{rms} random vibration profile from 5 to 1000 Hz (Dodds and Ward, 2005).

3 PHYSICS OF FAILURE IN ELECTROMECHANICAL SYSTEMS

In electromechanical systems, the components most susceptible to fatigue damage due to vibration are electronics (Li, 2002). In fact, electronic component stress failure is the primary concern in aerospace, automotive and military vehicles due the extremely harsh environmental conditions (Li, 2002) and (Pecht *et al.*, 2001). These operating conditions can instigate failure modes such as open electrical leads and changes in the operating parameters that are outside the specification limits. These failure mechanisms are phenomena that either occur instantaneously or develop over time. The effect of the vibration stresses can be manifested as degradation in performance or as a gradual loss of durability of the elements in the product. Accumulated damage is another measure of degradation that often cannot be directly detected by performance loss. Damage can occur and accumulate during the life phases and affect the reliability of the electronic hardware (Pecht *et al.*, 2001).

With the remarkable advances made in commercial electronics for computing, telecommunication, and other applications, it is becoming progressively more beneficial to use such components in military applications for improved computational performance, reduced cost, on-demand availability, to address obsolescence, and to have state-of-the-art capabilities. This current movement of using commercial-off-the-shelf (COTS) electronics and electronic packages for military applications has lead to overwhelming concerns about their reliability in harsh battlefield environments.

It is understood that one of the most predominant failures in electronics is due to solder joint fatigue. Analysis of solder joint stresses associated with vibration is widely seen in the literature: Liu *et al.* (2006) and Yang *et al.* (2007). In assessing the solder joint fatigue failure under vibration, it is important to know the vibration characteristics of the electronic system and the mechanical behavior of the individual components. This may involve observing failure of solder joints experimentally and incorporating a solid joint mechanical behavior into analytical and numerical models. Analytical models can help to quickly identify the parameters of interest in a vibration analysis and are computationally less intensive than numerical models. Among the available analytical models are those by Suhir (1998), developed to assess vibration induced failures in electronic packages. Barker *et al.* (1993) developed analytical models for vibration induced failures in surface mount components.

In Surface Mount Technology (SMT), the reliability of solder joints is extremely critical, since the solder joint provides electrical and thermal continuity as well as structural integrity (Lau *et al.*, 1996) and (Jih and Jung, 1998). However, in most solder joint reliability analyses, in both industry and academia, the main focus is on the uniaxial deformation behavior when, in reality, the solder joints are subjected to complicated multiaxial stressing and straining. Both AMSAA and CALCE amongst others recognize the need to measure the basic mechanical properties of solder alloys under multiaxial loading and at the same time to develop a comprehensive constitutive model for reliability and failure analysis is apparent. However, the multiaxial constitutive descriptions for solder alloys are very limited, especially the time-dependent constitutive descriptions for lead-free solder alloys. A reliable multiaxial time dependent constitutive model for solder alloys is fundamental to the design of reliable electronic joints. In particular, kinematic hardening should be taken into account.

Some of the limited studies investigating the vibration durability of solder were performed by Zhou *et al.* (2009) at CALCE. They examined the vibration durability of Sn37Pb and SAC305 (lead free) solders using a combination of harmonic excitation tests and finite element modeling. The analysis was conducted using a time-domain approach, to quantify fatigue damage caused by harmonic excitation at the first natural frequency of the test vehicle. Zhou and Dasgupta (2007) concluded that the SAC305 solder was found to have lower fatigue durability than the SnPb solder under narrow-band harmonic excitation. Furthermore, failure analysis produced in their investigation revealed that there are two competing failure modes, one in the solder and another in the copper trace under the component. The solder fatigue properties were extracted with the help of Finite Element Analysis (FEA). Nonetheless, further investigation is warranted to understand the mechanics of these competing failure modes under random vibration conditions.

4 TESTING METHODOLIGES

4.1 *Hydraulic Simulator*

For more than forty years, the automotive industry has relied on the four-post hydraulic simulator as the standard method for validating vehicle durability (Dodds and Ward, 2005) and (Awate *et al.*, 2007). It is the simplest and cheapest test configuration for conducting a complete vehicle vibration evaluation. It is comprised of four vertical servo-hydraulic actuators which excite the test vehicle through its tires as shown in Figure 3. The input can represent the road surface or some deterministic function that can be used to evaluate the vehicle’s dynamics and its structural properties. In general, the test vehicle’s vertical wheel accelerations and the wheel-to-body displacements are measured on the proving ground then reproduced on the simulator. It is often assumed that the remainder of the vehicle responds as it does on the road (Awate *et al*., 2007). This, of course, applies only to components influenced by vertical loading. Consequently, this method introduces three major sources of errors. The first error is the inability to introduce the effect of the vehicle’s rolling tires in terms of stiffness and damping. The second error is the lack of lateral and fore-aft inputs to the vehicle. Finally, the four-post hydraulic system’s frequency range is limited to a low frequency range, in general 1-50 Hz (Dodds and Ward, 2005).

Figure 3- Hydraulic Simulator, from Awate et al., (2007)

These limitations create a high level of difficulty in measuring, predicting and modeling high-frequency vibration in automotive subsystems, which are the major contributor to irregular wear in automotive components (Delamotte *et al.*, 2008). These high frequencies can easily generate other high frequencies caused by critical rotating speeds, random vibration, noise radiation and loss components that can potentially create further damages especially to electronics. These frequencies are very easily transmitted from the chassis to the vehicle body and eventually to subsystems (Liu, 2008).

Some researchers have suggested modeling the dynamics response of the vehicle subsystems. This approach, however, can be an arduous task (Li, 2001). The main reason for this lies in the fact that the automotive chassis and body are a large complex system. The reaction forces and vibration velocities depend not only on the strength of excitation within the chassis but also on the coupling of the chassis and the auto body. Thus, one has no choice but to count on engineering judgment in estimating the boundary conditions and systems inputs. Moreover, an auto body cannot be modeled very well using FEA up to mid-frequency range due to the higher modal density. In this situation, it is recommended to take a more practical approach by using experimental Frequency Response Function (FRF) data to represent the body in the middle frequency range and then combine it with the FEA models.

4.2 *Repetitive Shock Shaker (HALT)*

The conventional design approach in electronics packaging is an iterative loop, i.e., design-prototype-test-fix. This process requires long cycle time and high expenses related to physical prototyping and testing. The lack of prediction capability of a product's reliability leads to deficiency in its design. This hurdle can be overcome with Repetitive Shock (RS) shaker or Highly Accelerated Life Testing (HALT) during the prototyping and qualification stages. The idea of HALT is to conduct highly accelerated tests during the design process with the intent to stress the product to failure in order to assess the design robustness and weakness through rigorous root cause analyses. The purpose of the test is to identify design weaknesses that, due to variability, would eventually show up as failures when larger quantities of the product are used within the design limitations. This method is performed by applying accelerated stresses to determine the operating and destruct limits of the design.

Figure 4- RS Shaker at CALCE

HALT testing may subject the test sample to stresses higher than those encountered in the field during shipping, storage, or operation. Because failure of the product during HALT cannot be precisely correlated to lifetime in the field, the rule of thumb is to continue improving the product performance under HALT as far as feasible. As commonly occurring failure mechanisms are accelerated under higher stresses, any improvement under HALT usually leads to improvement under field conditions (Dasgupta and Pecht, 1991) and (Pecht *et al*, 2001). The test is performed in a HALT chamber which typically has a broad spectrum of vibration energy between 10 Hz to above 5,000Hz and runs from 1 up to 150 G_{rms}. The initial stress and order of increase or decrease for the various stress levels are product dependent. The testing process, in general, begins well within the design envelope and cycles temperature from high to low while simultaneously inducing vibration by six-axis pneumatically driven hammers, as shown in Figure 4.

HALT does not provide clear knowledge of the failure mechanisms. This is because it provides mostly a qualitative rather than a quantitative understanding of the failures due to two major limitations. First, the only input that can be controlled during vibration testing is the G_{rms} in the vertical direction (or Z direction). Thus, it is impossible to control the shape of the excitation Power Spectral Density (PSD) profile, as shown in Figure 5. Secondly, since the chamber employs six-axis pneumatically driven hammers, it is impossible to independently control each DoF. CALCE has shown that the coherence between the axes is nonexistant, as shown in Figure 6 (Choi et al., 2009). Thus, it is impossible to identify the most dominate failure mechanism or the DoF that instigates the most damage to the components. Therefore, it is difficult to establish a quantitative relationship between performance in the field and performance in the test.

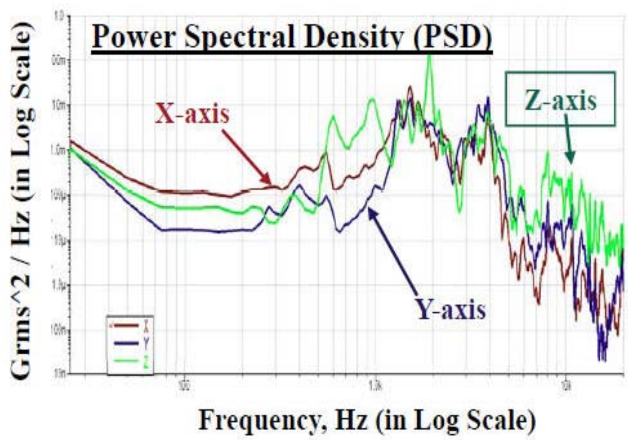

Figure 5- PSD in RS Shaker (Choi et al., 2009)

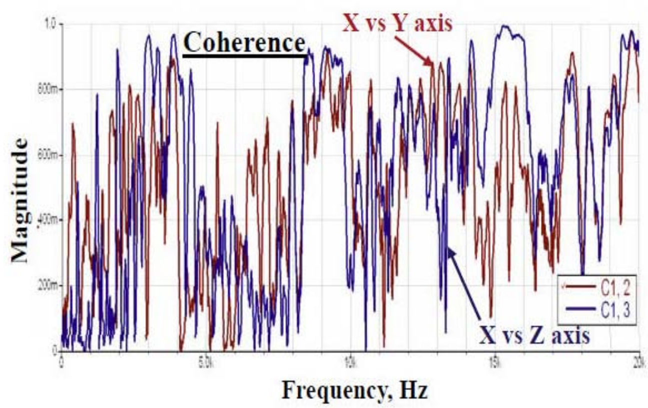

Figure 6- Coherence in RS Shaker (Choi et al., 2009)

4.3 *Multiaxial Electrodynamic Shaker*

Due to the limitations of uniaxial electrodynamic shakers, hydraulic actuators and HALT, CALCE and AMSAA are investigating the possibility of utilizing multiaxial electrodynamic shakers. The objective is to study the differences in failure modes and fatigue life for multi-axis loadings versus single-axis inputs by utilizing multiaxial electrodynamic shakers.

The multiaxial electrodynamic shaker at CALCE was developed by TEAM Corporation (Choi et al., 2009). It consists of eight plane actuators and four out of plane actuators underneath the shaker table, as shown in Figure 7. The twelve electrodynamic shakers are mechanically coupled to the table. This architecture allows the shaker to produce a true six DoF vibration environment. Each axis has four shakers with 200lbf rotation per axis. The excitation limit is up to 30Gs with 0-3000Hz. Unlike other testing methodologies multiaxial electrodynamic shakers will provide a clearer knowledge of the failure mechanisms in electromechanical devices. This is because it provides both qualitative and quantitative understanding of the failures not present in single-axis excitation. The inputs can be controlled for all as demonstrated by CALCE, Figure 8. This is because the twelve shakers can be excited independent of each other. Figure 8 shows excellent control of the shape of the excitation PSD profile. CALCE has also shown that the coherence between the axes is excellent as shown in Figure 9. Therefore, it is possible to identify the most dominate failure mechanism or the DoF that instigates the most damage to the components. This will aid AMSAA in establishing a quantitative relationship between performance in the battlefield and performance in the test.

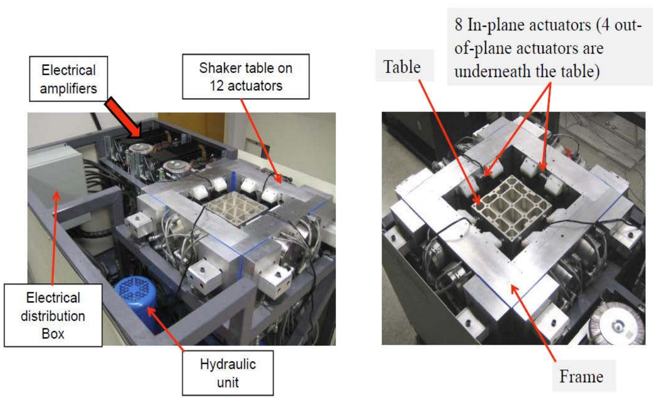

Figure 7- Multiaxial ED Shaker at CALCE

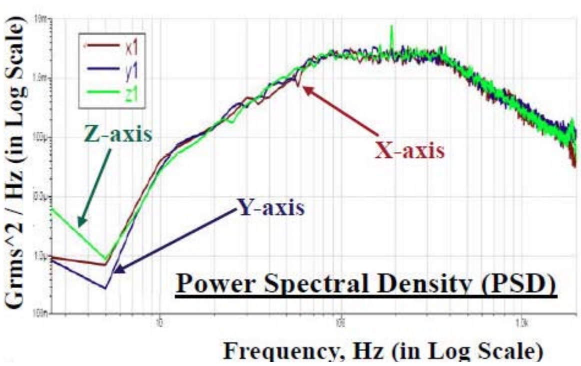

Figure 8- PSD in Multiaxial Shaker (Choi et al., 2009)

5 OUTCOMES

It can be concluded that it is essential to understand the structural characteristics of electronic devices in order to correlate the defects with the dynamic responses. As mentioned above, the main challenge in electronics packaging is the prediction of the reliability and lifetime of the critical components. Therefore, it is imperative to identify the failure mechanisms of the components through experimental analysis. However, the experimental approach has to emulate the real world operational conditions, which includes simulating multi-DoF dynamic loads. This involves experimentally measuring the transient in-plane and out-of-plane displacement responses which can be accomplished with the aid of a multiaxial shaker.

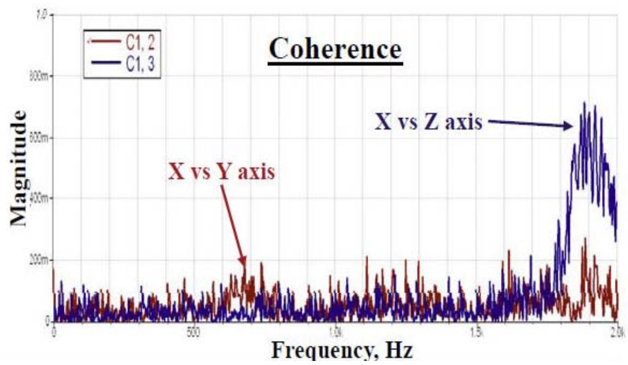

Figure 9- Coherence in Multiaxial Shaker (Choi et al., 2009)

Both Aberdeen Test Center (ATC) and the AMSAA Reliability Branch recognize the need to update MIL-STD-810G to include enhancements to simultaneous multiaxial vibration standards. CALCE will investigate the fatigue damage in electromechanical assemblies due to multi-axial excitation encountered in the battlefield. The goal is to capture unforeseen design defects and to ruggedize military devices for fatigue damage caused by unexpected synergies between modes excited by different axes. This investigation will then be utilized to enhance and improve MIL-STD-810G Method 527 through lessons learned. The study will also provide means to validate and improve existing physics of failure models.

ATC, AMSAA and CALCE believe providing multiaxial testing standards will also assist military contractors in producing more cost effective and reliable systems for our warfighters. It will also provide the warfighters with reliable and robust devices to guarantee their safety.

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